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# Real options theory applied to electricity generation projects: A review

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ABSTRACT

Real options (RO) theory is well known for enhancing the value of projects under uncertainty. This is achieved by modelling the flexibility that managers possess to adjust the projects in response to changes in their environments. Based on this, RO theory could be used to tackle current energy and environmental issues by enhancing the value of electricity generation projects (EGP), especially renewable energy projects (REP).

The potential of RO theory to increase the value of EGP and REP has been a driver for new research in the topic. However, existing literature is still scarce, diverse, and tends to neglect the state of the art of RO theory (e.g. RO in the design of projects). RO studies tend to ignore the use of RO in the design of projects as they are difficult to formulate without the help of experts on the projects' designs.

This paper aims to encourage novel research in the application of RO theory to EGP and REP. For this purpose, a critical review of RO theory, its state of the art, and its applications to EGP and REP is presented. This review identifies current areas of interest and gaps in knowledge in this research area. It is concluded that new and novel RO research should address the state of the art of RO theory, and uncertainties that are exclusive for specific types of projects. This future research will require the involvement of electrical engineers specialised in the design of EGP and REP.



**Contents**



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## 1. Introduction

Real options (RO) theory is the application of concepts from financial options valuation for the assessment of real life projects [1,2]. The purpose of RO is to identify and assess manager's options to adjust projects in response to the evolution of uncertainty. That is, RO theory acknowledges the ability of managers to modify their projects with the objective of maximising profits and minimising risks in an ever changing world. The proper application of RO can enhance the expected value of projects under uncertainty. This makes RO theory attractive for the assessment of projects such as electricity generation projects (EGP) and renewable energy projects (REP)[1] .

The importance of EGP and REP has been brought to the fore by environmental concerns and the global dependence on electricity. It is therefore important to encourage investments in renewable generation projects. This could be achieved by applying RO theory to increase the economic value and attractiveness of these projects.

In the last few years, an increasing volume of research has focused on the application of RO theory to EGP and REP. The results so far are encouraging as the use of RO theory has been shown to improve the economic performance of this type of projects. On the other hand, existing RO literature addressing EGP and REP is still scarce as well as diverse and tends to neglect interactions between and RO in the design of projects [3–5]. That is, (i) there is little research on the topic, (ii) the research area comprises many different generation technologies (e.g. gas and wind) and types of RO (e.g. wait and expand), and (iii) there is little research on options interactions and RO in the design of projects, namely the state of the art of RO theory. The state of the art of RO theory tends to be ignored due to its complexity, and because RO in the design of projects can only be formulated with the aid of specialists in the technical aspects of these projects.

Based on this information, there are many research opportunities concerning the application of RO theory to EGP and REP. This paper aims to motivate novel research in this topic by highlighting current areas of research and gaps in knowledge. The novel research must involve RO specialists as well as experts in the design of EGP and REP.A critical review of RO theory, its state of the art and applications to EGP is provided. The objective is to illustrate the diverse applications of RO theory to EGP, highlight topics of research interest, and identify gaps in knowledge. It is important to note that most, if not all, RO literature concludes that RO increase the benefits or reduce the costs of EGP. This is not described in the literature surveys for simplification purposes.

The paper is structured as follows: Section 2 provides a general explanation of RO theory and its current state of the art. Section 3 presents a review of the application of RO to EGP. Section 4 extends the review to include REP and EGP subject to environmental policies. Section 5 concludes this work by presenting the areas of research interest that are highlighted by the literature surveys.

## 2. Real options theory

RO theory postulates that (i) projects under uncertainty might possess RO, (ii) the projects become flexible if the RO can be identified and timely executed, and (iii) flexibility adds value to the projects. To better explain these ideas, let us elaborate on the terms RO and flexibility.

A real option is the right, without obligations, to defer, abandon, or adjust a project in response to the evolution of uncertainty [2]. Hence, a real option is any action that project managers can use to modify a project. Flexibility refers to the capability of managers and the necessary characteristics of the project that enable RO. In other words, the project is flexible if it can be deferred, abandoned, or adjusted in another manner that can be afforded by managers [4]. A project that has RO (e.g. secure free space to allocate additional capacity) is not deemed flexible when the managers cannot identify the option or are unable to implement it (e.g. not enough capital to pay for the capacity expansion). A flexible project can be adjusted by managers to maximise profits and/or minimise losses in different scenarios. Thus, flexibility increases the expected value of projects.

In summary, RO theory can be defined as an approach to engender flexibility in projects. RO theory aims to identify, formulate, and assess actions that can be used by managers to adjust projects in a changing environment. For this purpose, RO theory relies on the ideas and tools developed for financial options valuation.

### 2.1. Financial options valuation

Financial options are contracts between two parties, typically consumers and sellers, which provide the right without obligation to trade products at a specific time for a predetermined price [6]. This is similar to RO that provide the right to adjust a project at a specific time for a cost that reflects the resources required to make this modification. Based on these similarities, it is logical to address RO with the tools and ideas that are already well established for financial options valuation [5–7].

Several approaches from financial options valuation have been extended for the assessment of RO. Some of these approaches are (i) partial differential equations (PDE), (ii) trees and lattices, and (iii) simulations (sim). A brief description of these approaches is provided below; a deeper analysis is beyond the scope of this work but it can be found in [2,5,6].

1) *Partial differential equations*: PDE have to be formulated for the assessment of specific RO under fixed assumptions [2]. This approach is highly accurate and can be computationally inexpensive for simple options. However, a new set of PDE has to be formulated whenever the RO or assumptions change. This can be time consuming or even unfeasible for complex options [5]. The most widely used set of PDE is the Black and Scholes formula [8,9].
2) *Trees*: Trees or lattices simulate the evolution of uncertainty in discrete scenarios [2]. This approach facilitates the modelling of multiple interrelated options. Nonetheless, it is less accurate than PDE and can become computationally expensive or prohibitive for large amounts of scenarios. The most widely used tree approach is the binomial tree [10].
3) *Simulations*: Simulations can be used to model the evolution of uncertainty. This is a robust approach that can handle many types of RO, however, it tends to be computationally expensive. A well known simulation approach is the least squares Monte-Carlo simulation [11].

### 2.2. Barriers for real options theory

RO theory has proven to be suitable for the assessment of projects under uncertainty. Nevertheless, the acceptance of the theory has been slow manly due to several misconceptions about RO [4,12]:

[1] REP are EGP based on renewable energy sources.

1) RO theory is a black box difficult to understand: the initial RO literature was heavily based on finance theory and described with finance jargon. In addition, RO studies used to rely mainly on PDE that were only applicable under specific assumptions. These factors made RO theory difficult to apply for people without a strong background in Finance. In 1994 this changed due to a book published by Dixit and Pindyck which explained RO theory in a simple and clear manner [2]. Nowadays, there are many publications meant to make RO theory accessible, as well as several RO tools and software that can be easily applied under a wide range of circumstances [2,4,6].
2) RO theory is just a tool used to exaggerate the value of projects: As RO theory has the potential to increase the value of projects, it may be perceived as a tool to wrongly inflate the value of projects. This is a mistake because RO theory only develops the value of flexibility within projects. If the project is flexible, neglecting its flexibility would undervalue the project. If the project is not flexible, RO theory cannot increase its value [4].
3) RO theory favours risky projects: RO are used to adjust projects in response to the evolution of uncertainty. As a result, RO become more valuable when uncertainty is significant. This may cause the misunderstanding that RO favours risky investments. However; the reality is that under high uncertainty levels, it is vital to possess the flexibility to reduce losses in negative scenarios and maximise profits in beneficial scenarios [4].
4) RO theory is only applicable for tradable assets: There is a general misconception that RO theory is only applicable to the assessment of options that are observable in a market (e.g. stock and power markets). This is not true, and has been proven by several authors [13,14]. Even if the option is not tradable in a market, it can be assessed as long as its uncertainty can be characterised.
5) RO do not work in practice: RO theory relies on the idea that managers can use the options to hedge the risks and enhance the expected value of projects. Nevertheless, RO theory is ineffective if the manager refuses to exercise any options. In practice, project managers might not be willing to exercise some options, especially when that involves abandoning projects [12]. As a result, RO theory is not valuable for these projects. This problem can only be solved if project managers understand the value of flexibility derived from RO theory, and commit to apply the theory.

There are still many barriers to overcome before RO theory is fully accepted in practice. Nevertheless, increasing research in the theory, such as this paper, are expected to improve the practical applications of the theory and make it more accessible, understandable, and thus popular.

### 2.3. State of the art of real options theory

RO theory was developed in 1977 due to the increasing application of financial options valuation theory for the assessment of real projects [15]. This application was motivated by (i) growing dissatisfactions with traditional methods for the assessment of projects under uncertainty [16,17], and (ii) novel innovations in financial options valuation theory brought about by the introduction of the Black and Scholes formula [8,9].

Initial RO literature did not describe the options available for projects, nor provided all the tools needed to assess options. As a result, early RO research focused on the identification of new types of options, application of the theory to different areas of knowledge, and development of new RO tools.

The different RO proposed at the time could be classified as [1,5] (i) defer RO, which are alternatives to delay investment decisions with the objective of gathering information; (ii) time to build RO, which entails the construction of a project in several stages; (iii) alter operating scale RO, which are options to either expand or shrink a project; (iv) abandon RO, which entails selling the project if it generates losses; (v) switch RO, which are alternatives to change the output or input mix of the projects; and (vi) growth RO, which are options to invest in pilot projects before building a large project.

Several RO tools were developed to assess the aforementioned options. These tools were mainly PDE derived specifically for each type of RO and underlying assumptions. That is, RO theory focused on the assessment of options in isolation under specific circumstances.

In the mid 1990s, Trigerogis [1,5] recognised that, even though RO research concerning options in isolation was valuable, it was not applicable in real life conditions where options are interdependent. He highlighted that RO theory would only be applicable in practice if it could model RO interactions with other RO, financial options, and projects. In order to promote this type of research, the RO group was founded and the annual international RO conference was established [18,19]. These changes in the scope of RO research aimed to expand RO theory from a mere academic exercise to an approach valid in real life conditions.

By 2002, a handful of researchers had followed Trigeorgis recommendations and researched RO interactions, including interactions between the options and the design of projects. The latter application of RO theory was named RO in the design of projects by Wang and Neufville [20]. RO in the design of projects are options embedded in the specific technical and technological characteristics of projects. Thus, these RO can be designed into projects.

Before going further, it is important to clarify the difference between generic RO and RO in the design of projects. Generic RO can be applied to different types of projects regardless of the characteristics of the project [20]. A few examples of generic RO include the defer and time to build RO. RO in the design of a project take into consideration the specific characteristics of the project [21]. For example, a real option in a nuclear plant is the alternative to build the infrastructure required to connect an accelerator to different reactors [22].

The use of RO in the design of projects allows RO theory to identify sources of flexibility that might be exclusive to a specific project. Thus, the theory could be used to enhance the value of specific types of projects, such as EGP and REP. However, RO in the design of projects are highly complex, path dependent, and can only be identified by experts in the design of the projects. As a result, the propagation of the use of these RO has been slow [23,24].

The greatest barrier hampering the use of RO in the design of projects is the lack of knowledge. It can be said that research concerning RO in the design of projects has been limited mainly because project managers do not understand the design characteristics of systems, and project designers are not familiarised with RO theory [25]. This emphasises the importance of involving experts in the design of systems in RO research.

Eventually, the applications of RO theory in the design of projects will become better known. For the time being, it is slowly gaining acceptance, and it has been applied to a variety of projects including mines, satellite constellations, enterprise architecture, unmanned air vehicles, among others [26–29]. Additionally, a general explanation of the use of RO theory in the design of engineering systems is now available in a book [4], which should facilitate its propagation.

As a concluding remark, the state of the art of RO theory comprises practical applications in which options interact, and the design of the projects plays an important role. The propagation

of the state of the art of RO for the assessment of EGP and REP requires the involvement of electrical engineering experts in the design of the projects.

## 3. Real options for generation projects

The advent of deregulation of the power sector in many countries in the mid 1980s exposed EGP to uncertainties associated to competition and electricity price variations. RO theory is attractive for the assessment of EGP in this uncertain environment [30–32]. Regardless, there is still little literature on the topic [3]. This suggests that new research in this area would be valuable, particularly if it addresses the state of the art of RO theory. Furthermore, this new research can become more attractive by exploring the existing areas of research concerning EGP.

This section provides a critical review of literature concerning the application of RO theory to EGP. The objective of this review is to discuss the different applications of RO theory at different stages of the EGP, identify the uncertainty sources that can affect the projects and review how RO can affect the competitiveness of EGP. This information emphasises the applicability of RO theory to EGP as well as several areas of research in this topic. Later on, in Section 4, the review will be extended to focus on a particular type of EGP, namely REP.

### *3.1. Application of real options at different stages of generation projects*

RO theory can address options at different stages of projects, specifically, at the (i) planning, (ii) operational, and (iii) design stages. Most existing RO literature focuses on the planning and operational stages.

At the planning stage, RO theory is used to assess investment decisions. That is, to decide if managers should invest, when they should invest and in which projects. The most common options used at this stage are the defer RO.

Barria and Rudnick [33] have studied the benefits of defer RO for investment decisions on different types of EGP subject to electricity price uncertainty. This work illustrates the value of the defer RO for isolated projects. A more practical study that includes option interactions was presented by Takashima et al. [34]. This study combines the defer options with options to invest in EGP with different capacities. The RO study can be further improved by addressing the limitations of the power system rather than just the characteristics of the EGP. Zhou et al. [35] assess investment decisions on EGP subject to the power, voltage, and line capacity constraints of the IEEE 30 bus system. Another improvement to the RO study can be the use of multiple objectives. Martinez-Cesena and Davalos [36] study investment decisions on distributed EGP located in a real distribution network and taking into consideration RO, financial options, and multi objective criteria.

At the operational stage, it can be assumed that the project already exists. This allows the RO study to focus on alternatives to adjust the project, such as a generic alter operating scale and abandon RO. It is also possible to formulate custom options, such as the use of different fuels for the generators. If it is assumed that the project does not exist, RO theory can be applied at both the planning and design stages.

The use of generic RO at the operational stage (i.e. switch RO) can be seen in Nihat [37]. This work analyses the option to generate power using different available EGP in a vertically integrated environment. That is, the study consists on a simple economic dispatch based on RO theory. The use of custom made RO can be seen in Nansheng et al. [38]. They model a profit loss insurance mechanism as an option that allows EGP to share market risks. The last two references assess RO in isolation, which is impractical. A more practical work that combines generic and custom RO is presented by Takashima, et al. [39]. They investigate the operation of a nuclear plant that can be adjusted with generic RO to abandon the project and custom RO to lengthen the lifetime of the plant.

The application of RO theory at both the planning and operational stages of projects can be seen in Min and Wang [40]. This study concerns investment decisions on two market interrelated EGP. The managers have RO to defer investment decisions, as well as options to alter the operating scale of the EGP. This analysis was later extended for any number of market interrelated EGP [41].

The use of RO at the design stage of projects is part of the state of the art of RO theory. At this stage, RO tend to be either custom made or involve variations of generic RO that impact the design of projects (e.g. the information associated to the use of defer RO can be used to optimise the design of a project).

Literature about the application of RO in the design of EGP is still rare. Cardin et al. [22] assess investment decisions on a nuclear EGP subject to technology uncertainties. The study considers a typical growth option, as well as custom RO in the design of the project to build the infrastructure required to connect each accelerator to any reactor, and add an extra reactor. Other examples of RO in the design of EGP include Wang and de Neufville [21,42,43] who study RO in the design of hydropower projects, and Martinez Cesena and Mutale [44–46] who study RO in the design of hydropower, wind power, and solar photovoltaic (PV) projects. These works address REP and will be discussed in Section 4.

The literature reviewed in this section shows that (i) the scope and applicability of RO theory varies when applied at different stages of EGP, (ii) the studies can rely on well established but generic RO and/or RO custom made for specific projects, and (iii) the research can be improved by modelling option interactions, power network constraints, and multiple objectives, among other factors.

### *3.2. Uncertainty sources that affect generation projects*

RO theory is based on the idea that projects can be adjusted in response to the evolution of uncertainty. Therefore, a requirement for the use of RO theory is the existence of uncertainties that affect the performance of projects.

Before proceeding, it is convenient to classify the uncertainties that affect EGP as external and internal uncertainties. External uncertainties affect many types of EGP (e.g. the price of electricity), whereas internal uncertainties only affect a specific type of projects (e.g. the wind speed). These uncertainties can be modelled as exogenous or endogenous factors. An exogenous uncertainty source is independent of projects (e.g. values set by the government), whereas an endogenous uncertainty source exhibits interrelations with the performance of projects (e.g. market values).

Most of the literature presented so far reflects external and exogenous uncertainties. This is the easiest type of uncertainty to handle as it affects most, if not all, projects and it does not exhibit interrelations with their performance.

Examples of internal uncertainties are rare in RO literature. A few examples of these uncertainties include generation technology uncertainties, as already alluded to in Cardin et al. [22], and renewable source uncertainties, as will be discussed in Section 4.

Uncertainties can be modelled as exogenous factors when the performance of the project cannot affect the uncertainty source (e.g. the sun radiation does not change regardless of the capacity

of a PV park), or the project is small enough to neglect its impacts on the uncertainty sources. The former assumption is used in Agusdinata [47] to model demand and electricity prices as exogenous uncertainties. The work investigates investment decisions on EGP taking into consideration RO to alter the operating scale of the project.

It might be unrealistic to model uncertainties as exogenous factors for the assessment of large EGP. Botterud et al. [48] and Gahungu and Smeers [49] discuss that investments in large amounts of generation can have a significant impact on the price of electricity. Therefore, the price of electricity should be modelled as endogenous uncertainty. Otherwise, the RO study cannot guarantee realistic results.

This literature highlights that (i) most RO research concerns external and exogenous uncertainties, (ii) there are uncertainties that only affect specific types of projects, namely internal uncertainties, and (iii) wrongly neglecting the use of endogenous uncertainty models can lead to unrealistic results.

### 3.3. *Effects of real options on the competitiveness of generation projects*

EGP that operate in a competitive environment are subject to uncertainties associated to electricity prices, demand, and other factors. As a result, the application of RO theory to this type of projects seems straightforward. As shown in Wang et al. [50], a RO framework can analyse investment decisions on EGP in a competitive market environment by addressing competition as a part of the electricity price uncertainty model.

The main benefit of RO theory is its potential to enhance the value of projects. In a competitive environment, this benefit should increase the competitiveness of a specific project. However, it can be argued that, if all projects rely on RO to enhance their value, their individual competitiveness will remain unchanged. This is not always true. Takashima et al. [51] study two competing investors that can build either nuclear or thermal EGP. Normally, nuclear power would be deemed more valuable, however; only the thermal power plants possess RO to stop production when the price of electricity is low. As a result, the thermal plants become more competitive.

As discussed previously, RO can be generic or custom made (e.g. RO in the design of projects), and can be used to adjust projects in response to external or internal uncertainties. Generic RO developed to manage external uncertainties can be applied to a wide variety of projects and do not affect the competitiveness of individual projects. Whilst, custom made RO and/or options designed to manage internal uncertainties will increase the competitiveness of specific type of projects.

Based on these ideas, and taking into account the growing environmental concerns, there is a significant research opportunity regarding the application of RO theory to enhance the financial value and competitiveness of REP.

## 4. Real options for generation projects under environmental concerns

Current environmental concerns and dependence on electricity highlight the importance of investments in REP. As a consequence, several governments (e.g. the UK) are (i) implementing economic support policies (e.g. feed in tariffs) to encourage investments in REP [52], (ii) promoting changes in the power sector to integrate renewable energies (e.g. enabling demand response) [53], and (iii) investing in the R&D of more financially attractive REP [54,55]. RO research can fit the latter application.

In this section, the RO literature survey is extended to account for EGP subject to environmental policies and REP, namely hydropower projects, wind farms, and PV projects. The purpose of this review is to highlight several areas of research interest related to the application of RO theory to low carbon EGP and REP.

### 4.1. *Generation projects subject to environmental policies*

Nowadays, EGP are exposed to uncertainties associated to environmental policies, such as carbon prices and real obligation certificates, among others. RO theory is an effective tool under these circumstances [56–59].

RO theory can be used to assess the effects of policies on specific EGP under particular conditions. Siquieira et al. [60] propose a RO framework to assess investment decisions on hydrothermal projects in Brazil. The framework assesses RO to register the projects in the clean development mechanism described in the Kyoto protocol [61]. More general RO literature tends to address the impact of policies on several types of EGP. Liu et al. [62] assess the case of an owner of a coal EGP that has an option to invest at any time in gas EGP with lower emissions. The results show that the value of such an option is highly dependent on the uncertainty of the emissions costs. Correia et al. [63] propose a general RO methodology to analyse multi-stage investments in EGP under emission costs uncertainty.

Apart from assessing a project under policy uncertainty, RO theory can also be used to assess the effectiveness of a policy. Scatasta and Mennel [64] analyse the success of renewable obligation certificates and feed in tariffs to promote investments in wind projects. The results show that the certificates can be the most effective policy to motivate investment in wind projects. Herve-Mignucci [65] presents a RO method to study the effects of carbon price uncertainty reductions and carbon price caps on new investments in different types of EGP. The results suggest that well defined caps are better suited to promote investment in low carbon EGP and REP.

This literature shows that RO theory is a valuable approach to assess the effectiveness of environmental policies and their impact on specific types of EGP. This will be an important area of research during the next decades, as many countries will be introducing environmental policies with the objective of mitigating climate change [66].

### 4.2. *Hydropower projects*

Hydropower projects are nowadays the most economically attractive types of REP. These projects are typically conventional (with storage) or run of the river (without storage) plants [67]. The output of a conventional plant is controllable and can be used to support EGP with intermittent outputs (e.g. wind farms). While, the output of run of the river plants is a function of intermittent water flows, which drives their managers to hedge risks using financial options and/or the support of other EGP.

Hedman and Sheble [68] study the use of pump storage hydropower and financial options to support wind generation. Xian et al. [69] explore the use of financial options to hedge the risk incurred by a run of the river hydropower plant. Kjaerland and Larsen [70] assess RO that enable conventional hydropower generators to store water by acquiring thermal power to supply the demand.

RO literature in this area presents a few examples of RO in the design of projects. Bockman et al. [71] propose a variation of an existing RO approach [72]. This approach is used to assess small hydropower projects and set the models required to use RO in the design of the project. For simplicity, the design is assumed fixed

(i.e. not flexible) and the use of RO in the design of the projects is left for future studies. Wang and de Neufville [21,42,43] propose a RO methodology for the identification and assessment of RO in the design of projects. This methodology is used to assess a series of hydropower projects. Later, Martinez-Cesena and Mutale [44], propose an improved version of Wang's RO methodology, and assess its performance using the same hydropower case study.

This literature illustrates that RO theory can be used to (i) hedge the generation risks of hydropower plants, (ii) assess the use of hydropower to hedge the risks of other EGP, and (iii) identify flexibility within the design of the plants (i.e. RO in the design of projects). The latter application involves a detailed modelling of the design of the projects, which requires knowledge about the technical characteristics of hydropower projects.

It is important to highlight that the uncertainty of hydropower plants is mainly a function of the water flows, which is an internal uncertainty. This suggests that REP are affected by at least one internal uncertainty, namely their renewable energy source. The existence of internal uncertainties and RO in the design of the projects means that new RO research can aim to increase the economic value and competitiveness of REP.

### 4.3. Wind power projects

Apart from hydropower projects, wind power projects are one of the most prominent REP [73]. The output of wind projects is a function of uncertain wind resources, which is an internal uncertainty that can be managed with RO theory. The long term output of these projects (e.g. annual out-turn) can be estimated deterministically [74]. As a result, most RO literature neglects the wind speed uncertainty to focus on external uncertainties such as the price of electricity.

Cheng et al. [75] evaluate wind projects based on their fuel and emission savings. Dykes and de Neufville [76] compare investments in large wind farms against investments in small wind projects with generic growth RO based on electricity price uncertainty.

The effects of wind speed variations in the short term (e.g. within a year) can be considered even if RO are not used to manage the wind resource uncertainty. Munoz et al. [77] use a RO approach to assess investment decisions on wind farms based on the electricity price uncertainty, whereas the operation of the farm is simulated hourly based on the variation of the wind resource. Zhou et al. [78] combine the wind speed and electricity price distribution to determine the revenues of a wind farm. This is used as an input for the RO assessment. Fleten and Maribu [79] present a RO study of investment decisions on small wind projects meant for own use. The variability of the wind speed and demand are modelled to determine the imports and exports of the project. Mendez et al. [80] model the wind resource variability using two different models; one for the annual variation and another for variations within a year.

Ultimately, RO can be developed based on the wind resource uncertainty and/or the design of a wind project. Martinez Cesena and Mutale [45] propose a RO framework for the planning and design of on shore wind farms based on the uncertainty associated to the characterisation of the wind resource.

This literature shows that existing RO research is just beginning to address internal uncertainties and the state of the art of RO theory. There is a need for RO research that explores (i) the design of different types of wind projects (e.g. small scale and off shore projects), (ii) different environments (e.g. a power market), and (iii) the wind resource and other internal uncertainties.

### 4.4. Photovoltaic projects

Among RO literature concerning REP, solar PV research is the scarcest [3]. Nevertheless, available works show the application of RO theory to manage external and internal uncertainties, and the design of the projects.

Hoff et al. [81] use a RO methodology to assess investment decisions on PV systems under electricity price uncertainty. The novelty of this approach is that instead of evaluating the RO based on a model for uncertainty, it determines the values of uncertainty that would render the RO valuable. Sarkin and Tamarkin [82], and Ashuri and Kashani [83] value RO based on an external uncertainty source (i.e. electricity price) and an internal uncertainty (i.e. the cost evolution of PV technologies). Martinez Cesena and Mutale [84] assess investments on domestic PV systems subject to uncertainties on the efficiency and costs of new PV modules. Both uncertainties are internal.

The use of RO in the design of PV systems can be seen in Martinez Cesena and Mutale [46]. This work presents a RO methodology for the assessment of potential changes in the design of off-grid PV systems based on the uncertain demand response capabilities of consumers.

This RO literature shows that the use of internal uncertainties is not uncommon for PV projects. However, existing literature in the area is limited and new research should continue to address internal uncertainties and the state of the art of RO theory.

This work presents several important gaps in knowledge concerning the application of RO theory to EGP and REP. A summary of the references reviewed throughout this work is shown in Table 1. The table provides (i) the authors of the work, (ii) the type of EGP that can be addressed with the RO approach[2], (iii) the stages of the project that are considered in the work, namely planning (plan), operational (op), and design (des), (iv) the uncertainty sources, (v) the approach used to model the RO, (vi) the year of publication, and (vii) the reference number.

## 5. Conclusion

RO theory can be used to enhance the financial value of projects under uncertainty such as EGP and REP. Currently, the state of the art of RO theory involves practical applications in which the options interact and the design of projects plays an important role.

The main barriers for the propagation of the state of the art of RO theory are misunderstandings and lack of knowledge regarding RO theory. The acceptance of RO theory is mainly hampered by the fact that project managers might not understand the rationale of the theory and believe that it is not applicable in practice. The application of RO to the design of projects is limited mostly because project managers do not understand the design characteristics of the systems, and project designers are not familiarised with RO theory. Accordingly, it is of great importance to produce new research that illustrates the diverse applications of RO theory, facilitates its understanding, and involves specialists in the system's technical aspects. This suggests that electrical engineers who specialise in the design of different types of EGP must get involved in new RO research.

Existing RO literature addressing EGP is scarce and, as a result, new research in the area would be valuable. There are several areas of research that can be explored to produce significant contributions to the area, particularly internal uncertainties and RO in the design of projects.

[2] RO that are applicable to many types of RGP are deemed generic.

**Table 1**
Summary of real options literature addressing electricity generation projects.

| Authors | EGP | Stage | Uncertainty | Tool | Year | Ref. |
|---|---|---|---|---|---|---|
| Barria and Rudnick | Generic | Plan | Price | Tree | 2011 | [33] |
| Takashima et al. | Generic | Plan | Price | PDE | 2010 | [34] |
| Zhou et al. | Generic | Plan | Price | Sim | 2007 | [35] |
| Martinez and Davalos | Generic | Plan | Price and cost | Sim | 2011 | [36] |
| Nihat | Generic | Op | Demand | Sim | 2011 | [37] |
| Nansheng et al. | Generic | Op | Price and cost | PDE | 2008 | [38] |
| Min and Wang | Generic | Plan and op | Price | Tree | 2000 | [40] |
| Min and Wang | Generic | Plan and op | Price | Tree | 2006 | [41] |
| Agusdinata | Generic | Plan | Price and demand | Tree | 2005 | [47] |
| Botterud et al. | Generic | Plan | Price | Tree | 2005 | [48] |
| Gahungu and Smeers | Generic | Plan | Price | PDE and sim | 2010 | [49] |
| Wang et al. | Generic | Plan | Demand | PDE and sim | 2006 | [50] |
| Liu et al. | Generic | Plan and op | Price, cost and policy | PDE | 2011 | [62] |
| Correia et al. | Generic | Plan | Several | Tree | 2008 | [63] |
| Herve-Mignucci | Generic | Plan | Price, cost and policy | Tree | 2010 | [65] |
| Fleten et al. | Generic | Plan | Price | PDE | 2007 | [72] |
| Takashima et al. | Thermal and nuclear | Plan and op | Price | PDE | 2008 | [51] |
| Siquieira | Hydrothermal | Op | Policy | Tree | 2011 | [60] |
| Takashima et al. | Nuclear | Op | Price | PDE and sim | 2007 | [39] |
| Cardin et al. | Nuclear | All | Technology | Tree | 2010 | [22] |
| Hedman and Sheble | Hydro and wind | Op | Wind | PDE and sim | 2006 | [68] |
| Xian et al. | Hydro | Op | Water and price | Sim | 2005 | [69] |
| Kjaerland and Larsen | Hydro and thermal | Op | Water and costs | Sim | 2009 | [70] |
| Bockman et al. | Hydro | Plan | Price | PDE | 2008 | [71] |
| Wang and de Neufville | Hydro | Plan and des | Price | Tree and sim | 2006 | [42] |
| Wang and de Neufville | Hydro | Plan and des | Price | Tree and sim | 2004 | [43] |
| Wang and de Neufville | Hydro | Plan and des | Price | Tree and sim | 2005 | [21] |
| Martinez and Mutale | Hydro | Plan and des | Price | Tree and sim | 2011 | [44] |
| Scatasta and Mennel | Wind | Plan | Policy and revenues | PDE | 2009 | [64] |
| Cheng et al. | Wind | Plan | Price, cost and policy | Tree | 2010 | [75] |
| Dykes and de Neufville | Wind | Plan and op | Price and policy | Tree | 2008 | [76] |
| Munoz et al. | Wind | Plan | Price | Tree and sim | 2009 | [77] |
| Zhou et al. | Wind | Plan | Price | Sim | 2007 | [78] |
| Fleten and Maribu | Wind | Plan | Price | PDE | 2004 | [79] |
| Mendez et al. | Wind | Plan and op | Cash flows | Tree and sim | 2009 | [80] |
| Martinez and Mutale | Wind | Plan and des | Wind | Tree and sim | 2012 | [45] |
| Hoff et al. | PV | Plan | Price | Tree | 2003 | [81] |
| Sarkin and Tamarkin | PV | Plan | Tech. and policy | Tree | 2008 | [82] |
| Ashuri and Kashani | PV | Plan | Technology and price | Tree and sim | 2011 | [83] |
| Martinez and Mutale | PV | Plan | Technology | Sim | 2012 | [84] |
| Martinez and Mutale | PV | All | Demand response | Tree and sim | 2011 | [46] |

In conclusion, the application of RO theory in the planning, operation, and design of EGP is an important area of knowledge that still needs significant research. This research will require the participation of RO experts as well as electrical engineers specialised in the technical and technological characteristics of EGP.

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